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Implement and soil condition effects on tillage-induced erosion

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Abstract

Water, wind, or tillage-induced soil erosion can significantly degrade soil quality. Therefore, understanding soil displacement through tillage translocation is an important step toward developing tillage practices that do not degrade soil resources. Our primary objective was to determine the effects of soil condition (i.e. grassland stubble versus previously tilled soil), opening angle, and harrow speed on soil translocation. A second field study also conducted on a Lixisol but only in the stubble field, quantified displacement effects of mouldboard ploughing. The field studies were located 12 km South of Évora, Portugal. Soil displacement or translocation after each tillage operation in both studies was measured using aluminium cubes with a side length of 15 mm as 'tracers'. Offset angles for the harrow disk were 20°, 44° and 59°; tractor velocities ranged from 1.9 to 7.0 km h^{-1} and tillage depth ranged from 4 to 11 cm. The depth of mouldboard ploughing was approximately 40 cm with a wheel speed of 3.7 km h^{-1}. The translocation coefficients for the two implements were very different averaging 770 kg m^{-1} for the mouldboard plough and ranging from 9 to 333 kg m^{-1} for the harrow disk. This shows that the mouldboard plough was more erosive than the harrow disk in these studies. All three variables (soil condition, opening angle, and tillage velocity) were critical factors affecting the translocation coefficient for the harrow disk. Displacement distances were the largest for compacted soils (stubble field), with higher opening or offset angles, and at higher velocities. The results also showed significant correlation for (a) mean soil displacement in the direction of tillage and the slope gradient and (b) soil transport coefficient and the opening angle. Our results can be used to predict the transport coefficient (a potential soil quality indicator for tillage erosion) for the harrow disk, provided tillage depth, opening angle, and tool operating speed are known.

Keywords: Soil translocation by tillage; Soil quality; Mouldboard; Offset disc harrow

1. Introduction

Tillage erosion is the down-slope displacement of soil through the action of tillage. The process was recently identified as an important factor in the study of soil erosion (Lindstrom et al., 1992; Lobb et al., 1995; Revel et al., 1993; Govers et al., 1994; Poesen et al., 1997; Turkelboom et al., 1997; Quine et al., 1999; Montgomery et al., 1999; Van Muysen et al., 1999), of soil constituent and amendment dispersion (Sibbesen, 1986; Monreal et al., 1995; Kachanoski et al., 1997; Quine et al., 1996) and for quantifying spatial variability in soil quality for agricultural lands (Kachanoski et al., 1985; Marques da Silva and Soares, 2001). Soil translocation is often expressed as the average length of displacement, which is equivalent to the volume of translocated soil per unit width of tillage divided by the depth of tillage. It is also expressed as a mass by

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Table 1
Tillage translocation coefficients

Implement	Remarks	Mean velocity ($km\,h^{-1}$)	Mean tillage depth (mm)	Tillage translocation coefficient (K) ($kg\,m^{-1}$)	Data source
Mouldboard plough	Stubble field	5.0	250	236	Govers and Van Muysen (1999)
Mouldboard plough	Stubble field	5.4	210	150	Govers and Van Muysen (1999)
Mouldboard plough	Stubble field	6.3	200	202	Govers and Van Muysen (1999)
Mouldboard plough	Contour stubble field	4.9	260	95	Govers and Van Muysen (1999)
Mouldboard plough		4.9	230	194	Heckrath and Sibbesen (1999)
Mouldboard plough		6.3	250	370	Heckrath and Sibbesen (1999)
Mouldboard plough	Contour	4.5	200	134	Kosmas (1999)
Mouldboard plough	Contour	4.5	300	253	Kosmas (1999)
Mouldboard plough	Contour	4.5	400	360	Kosmas (1999)
Mouldboard plough		4.5	180	65	Kosmas (1999)
Mouldboard plough		4.5	200	153	Kosmas (1999)
Mouldboard plough		4.5	250	161	Kosmas (1999)
Mouldboard plough		4.5	300	383	Kosmas (1999)
Mouldboard plough		4.5	400	670	Kosmas (1999)
Chisel plough	After hay harvesting	3.6	111	75	Marques da Silva and Soares (1999)
Chisel plough	After hay harvesting	3.4	189	27	Marques da Silva and Soares (1999)

multiplying the translocation volume by the bulk density of the tilled layer (Lobb et al., 2000).

Tillage erosion measurements in Europe (Marques da Silva and Soares, 1999; Govers and Van Muysen, 1999; Heckrath and Sibbesen, 1999; Kosmas, 1999) have shown that mouldboard ploughs can be 2–15 times more erosive than cultivators (Table 1), depending upon tillage depth and speed of operation. Such comparisons have also shown that the capacity for transporting soil down-slope is completely different for these two implements (Guiresse and Revel, 1995; Lindstrom et al., 1992; Lobb et al., 1992; Poesen et al., 1997; Sharifat and Kushwaha, 1998). Actual measurements of tillage erosion for harrow disks are limited, but it should not be assumed that the erosivity of this implement is the same as for other tillage tools.

There have been previous studies on tillage erosion, but additional information is needed to understand tillage translocation for a variety of soil conditions and implements. Our primary objective for this study was to determine the effect of different opening angles and implement speed on soil translocation in stubble and previously tilled soils. A second objective was to compare the erosivity of a harrow disk and mouldboard plough.

2. Materials and methods

2.1. Site

The field studies were conducted in a region of intensive dry land agriculture where winter cereals or rotations of cereals and leguminous crops are grown for animal feed. The farm, called “Cabanas,” is located near the village of “Vale Verde” 12 km South of Évora, Portugal. Initially, all of the experiments were to be conducted at one site, but due to normal farm activities it became necessary to shift the pre-tilled treatments to a second site. Prior to this experiment, both fields were in grassland for 4 years. The soil type at both sites is classified as a “Pgn—Solos Mediterrâneos Pardos de gneisses ou rochas afins’ according to Portugeese Classification or “LX-Lixisols” according to the FAO. The soil texture is loamy-clay-sand.

2.2. Soil movement measurements

To study soil movement, numbered aluminium cubes with a side length of 15 mm and an average density of 2665 $kg\,m^{-3}$ were used as tracers (Poesen et al., 1997). For the 24 harrow disk evaluations,

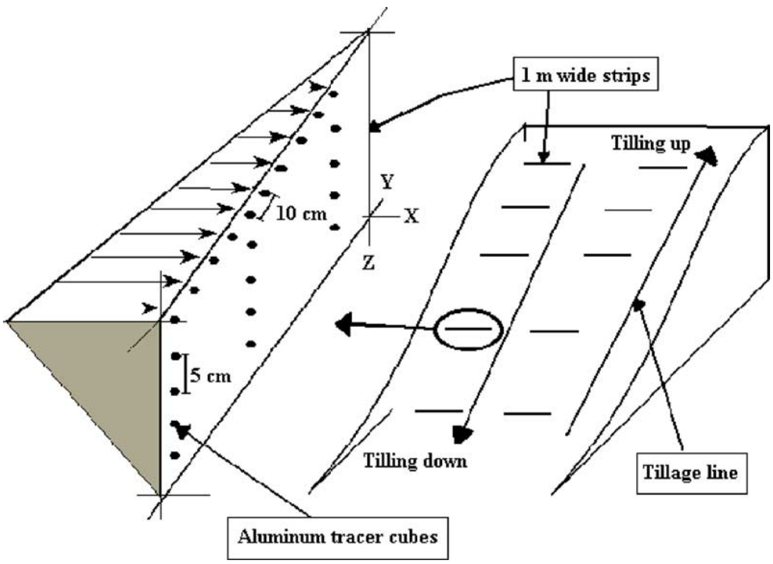

Fig. 1. Physical setup for the mouldboard plough evaluation of soil translocation.

cubes were inserted in 1 m wide strips at five locations at right angles to 12 tillage lines in each field (pre-tilled and grassland stubble). Tillage line is the number of necessary tillage pass's to plough the 1 m wide strips. For the two, mouldboard plough evaluations, cubes were inserted in 1 m wide strips at five locations at right angles to the two tillage lines, but only in the grassland stubble site. This created 120 measurement sites for disk harrow evaluations (12 'tillage lines' × 5 '1 m wide strips' × 2 'sites') and 10 for the mouldboard plough (2 'tillage lines' × 5 '1 m wide strips' × 1 'site'). At both sites, the spacing and location of the tillage lines was such that one pass was made up-slope and the second pass was made right next to the first in the down-slope direction (Fig. 1).

At each of the 1 m wide strips, 10 holes with a diameter of 25 mm were drilled at intervals of approximately 100 mm. For the disk harrow evaluations, each hole was 200 mm deep, while for the mouldboard plough sites each was 300 mm deep. Aluminum tracer cubes were placed in each hole, separated from each other by 50 mm of fine sand. The exact location of each numbered cube was precisely recorded using an automatic theodolite and microprism. This placement of tracers required 60 cubes per strip or 300 cubes per tillage line for the mouldboard plough evaluation (10 'holes' × 6 'cubes' × 5 '1 m wide strips') and 40 cubes per strip or 200 cubes per tillage line for the disk harrow evaluations (10 'holes' × 4 'cubes' × 5 '1 m wide strips').

After the tracer cubes were positioned in the soil, two tillage lines (10 '1 m wide strips') in the grassland stubble were tilled with a mounted, 3-point hitch, automatically reversing, 2-bottom general purpose mouldboard plough equipped with 360 mm (14 in.) plough shares. Tillage depth was approximately 400 mm and the average wheel speed was 3.7 km h^{-1}. A total of 120 sites (12 'tillage lines' × 5 '1 m wide strips' × 2 'sites') were tilled with a 24-offset disk harrow (12 plain coulters in the front gang and 12 plain discs in the rear gang) that has an adjustable opening angle of 20–60° between the two gangs. The harrow opening angle treatments that were used in this experiment were: 20°, 44°, and 59°. The harrow disk weighed 1992 kg with coulters that were 66 cm in diameter and spaced 24 cm apart. The harrow's working depth was approximately 50 mm for the 20° opening angle and 100 mm for the 44° and 59° angles. Wheel speed varied from approximately 1.9 to 7.0 km h^{-1} because the velocity of the tillage tool was difficult to control under different soil conditions. Initially, we attempted to have two velocity treatments in the experimental design. However, reproducing the same velocity, even with the same traction power is difficult, because in a loose soil the wheel-slipping coefficient is higher tilling up-slope as compared to down-slope. Furthermore, the average slope gradient at site 2, where the loose soil experiments were conducted, was greater than at site 1.

Immediately after the up- and down-slope tillage operations, the location of each displaced tracer was recorded by scanning the plough layer with a metal detector and carefully excavating up- and down-slope. For every strip, the tracer recovery rate exceeded 95%. The distance moved by each tracer cube in the up- and down-slope, as well as the mean displacement distance for the tracer populations in the up- and down-slope direction, were calculated. To compute the mean projected soil displacement distance, data from only those cubes in the tilled layer were used.

2.3. Calculations

Movement of soil by tillage was estimated in two ways. First, mean tracer displacement distances versus slope gradient were plotted. The slope gradients were considered negative when the tractor was moving down-slope and positive when moving up-slope (Lindstrom et al., 1992). Then, as proposed by Govers et al. (1994), a transport coefficient ($K = -DCB$) was calculated where D is the depth of tillage, C the bulk density of the soil before tillage and B the slope of the regression line between mean soil displacement distance and the slope gradient.

3. Results and discussion

3.1. Mouldboard soil translocation

The mean soil displacement caused by mouldboard ploughing (Fig. 2), verifies that this implement, over time, or averaged over a field, will produce a net down-slope displacement of soil caused by the tillage operation when the number of up- and down-slope passes were roughly equivalent. This occurs because the displacement of soil when the plough is travelling down-slope is greater than the displacement when the plough is travelling up-slope. Furthermore, due to the architecture of a mouldboard plough, our data verifies that this implement not only translocates soil in the direction of travel, but also shifts a more or less constant amount of soil perpendicular to direction of travel by about 450 mm (Fig. 3). The lack of statistical significance in the relationship between mean perpendicular soil displacement and slope confirms that the perpendicular movement is not slope dependent (Fig. 3). This is true for slope in the direction of tillage, but not necessarily for slope perpendicular to that direction.

With regard to the long-term impact of mouldboard ploughing on soil quality, Fig. 2 shows the mean soil displacement up- and down-slope in the direction of tillage while Fig. 3 shows the mean lateral soil displacement that the same operation has when tilling up- and down-slope. If during a second mouldboard operation the soil is displaced laterally in the direction opposite to the first operation, the net lateral soil

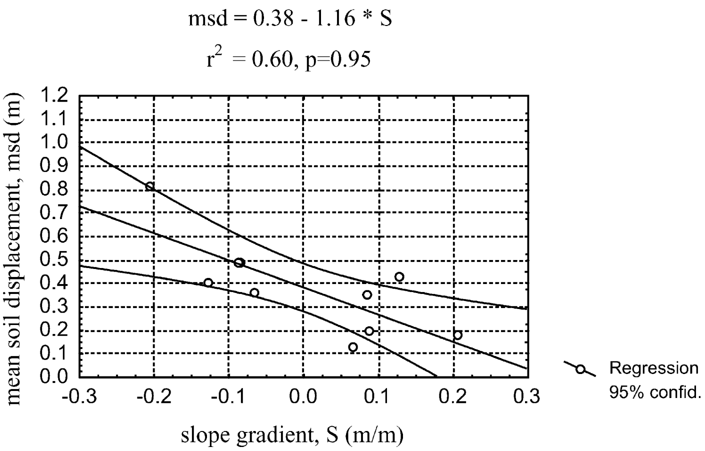

Fig. 2. Mean soil displacement distance for up- and down-slope tillage of grassland stubble with a mouldboard plough (Site 1).

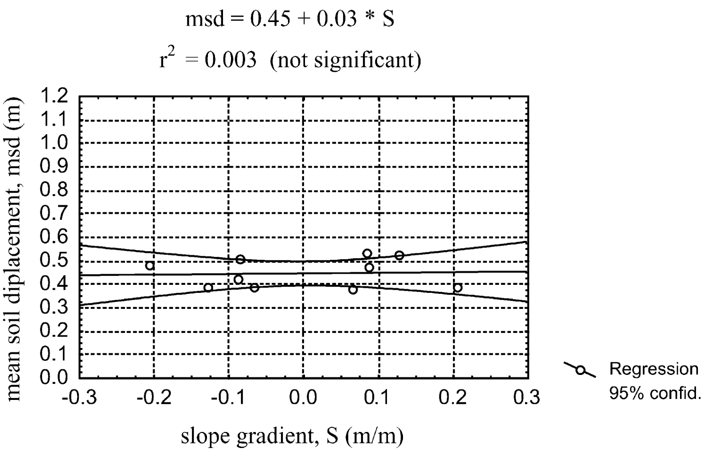

Fig. 3. Mean soil displacement distance perpendicular to tillage direction, for up- and down-slope tillage of grassland stubble with a mouldboard plough (Site 1).

movement would be approximately zero and the soil quality effect with regard to tillage lateral translocation would be minimal. However, if one displaces soil in the same lateral direction with every tillage operation, there will be a net lateral movement of soil each year. The soil movement in the direction of tillage will occur with every tillage operation (Lindstrom et al., 1992; Lobb et al., 1992).

For all the experiments we calculated a transport coefficient (K) using the same procedure as Govers et al. (1994). For the mouldboard plough experiment, our K value was 770 kg m^{-1} (Table 2), a value that was very similar to the one obtained by Kosmas (1999) (Table 1) for a similar tractor velocity and tillage depth.

3.2. Harrow disk soil translocation

For the harrow disk experiments with an opening angle of 20° (OA1), the average, minimum and maximum regression line slopes between mean displacement distance and slope gradient (Table 2) were −0.260, −0.326 and −0.143 m, respectively ($n = 4$, $s = 0.081$ m). For the transport coefficient K, the average, minimum and maximum values were 15, 9 and 18 kg m^{-1}, respectively, for $n = 4$ and $s = 4.267$ kg m^{-1}. These results are very similar and show that with a narrow opening angle soil translocation is not very high, presumably because the harrow disks do not disrupt the soil extensively with smaller cutting angles. This is probably the reason why farmers usually do not till the soil with this opening angle but rather prefer to use higher more aggressive tillage angles.

With an opening angle of 44° (OA2), the average, minimum and maximum regression line slopes between mean displacement distance and slope gradient (Table 2) were −1.412, −0.742 and −2.101 m, respectively, for $n = 4$ and $s = 0.589$ m. For the transport coefficient K, the average, minimum and maximum values were 183, 63 and 333 kg m^{-1}, respectively ($n = 4$, $s = 115$ kg m^{-1}).

Table 2 also shows that the mean displacement is greater in the stubble field than in the pre-tilled soil. However, the results were affected by the speed (e.g. 5.4 and 5.9 km h^{-1} were different from 1.9 and 3.5 km h^{-1}), slope (e.g. average slope of 0.126 and 0.123 were different from 0.187 and 0.192) and soil condition (i.e. grassland stubble versus pre-tilled) for the same opening angle (44°).

For the experiments with an opening angle of 59° (OA3), the average, minimum and maximum regression line slopes, between mean displacement distance and slope gradient (Table 2) were −1.603, −1.764 and −1.447 m, respectively ($n = 4$, $s = 0.159$ m). For the transport coefficient K, the average, minimum and maximum values were 205, 141 and 267 kg m^{-1}, respectively ($n = 4$, $s = 57$ kg m^{-1}).

These results confirm that soil transport coefficient was greater in the stubble field ($K = 267$ kg m^{-1}) than in the pre-tilled soil ($K = 141$ kg m^{-1}) for the same

Table 2
Slope of regression line between mean displacement and slope gradient, and mean transport coefficient

Trial[a]	Opening angle (°)	Soil condition	Slope ($m\,m^{-1}$)			Mean velocity ($km\,h^{-1}$)	Mean tillage depth (mm)	Mean soil displacement[b] (mm)	Bulk density ($g\,cm^{-3}$)	Intercept (m)	Slope[c] (m)	r^2	Tillage translocation coefficient (K) ($kg\,m^{-1}$)
			Maximum	Average	Minimum								
OA1V1	20	Stubble	0.166	0.112	0.060	5.4	40	60 (53/347)	1.65	0.064	−0.305	0.21	18
OA1V2	20	Stubble	0.160	0.116	0.096	7.0	40	50 (62/338)	1.65	0.052	−0.143	0.09	9
OA2V1	44	Stubble	0.162	0.125	0.081	5.4	100	360 (171/229)	1.65	0.357	−2.101	0.72	333
OA2V2	44	Stubble	0.142	0.126	0.091	5.9	70	380 (132/268)	1.65	0.378	−1.642	0.84	201
OA3V1	59	Stubble	0.148	0.123	0.088	3.1	110	390 (206/194)	1.65	0.390	−1.447	0.82	267
OA3V2	59	Stubble	0.148	0.115	0.070	4.8	80	470 (150/250)	1.65	0.466	−1.764	0.76	236
OA1V1	20	Pre-tilled	0.223	0.150	0.063	1.9	50	130 (72/328)	1.30	0.128	−0.267	0.26	16
OA1V2	20	Pre-tilled	0.250	0.191	0.062	3.4	40	110 (49/351)	1.25	0.115	−0.326	0.49	18
OA2V1	44	Pre-tilled	0.259	0.186	0.079	1.9	80	230 (136/264)	1.13	0.231	−0.742	0.82	63
OA2V2	44	Pre-tilled	0.232	0.187	0.043	3.5	110	400 (201/199)	1.10	0.397	−1.162	0.63	137
OA3V1	59	Pre-tilled	0.252	0.192	0.061	3.1	80	340 (169/231)	1.13	0.339	−1.486	0.87	141
OA3V2	59	Pre-tilled	0.239	0.195	0.066	3.4	90	360 (161/239)	1.13	0.363	−1.713	0.81	176
Mouldboard plough		Stubble	0.206	0.115	0.066	3.7	390	380 (575/600)	1.68	0.383	−1.158	0.60	770

[a] OA1, OA2 and OA3 (opening angles of 20°, 44° and 59°, respectively); V1 and V2 (lower and higher speed, respectively).
[b] The values in parentheses indicate number of tracers that have been moved and not moved.
[c] Slope of regression line from mean soil displacement vs. slope gradient.

tool speed (e.g. OA3V1 = 3.1 km h^{-1}) and at approximately the same tillage depth (80–110 mm) (Table 2). Our field observations also verified that larger clods were produced in the stubble field and that those clods travelled farther on the steepest slopes due to inertia. This was presumably caused by root density since there were no significant differences in soil water content between the stubble field and pre-tilled field. Nevertheless, it is hard to determine what specific factor caused the K values to be different since slope and tillage depth were both different.

Tillage speed appears to have had a contradictory effect depending upon the surface condition. Data from the OA2V1-stubble field (V1 = 5.4 km h^{-1}) and OA2V2-stubble field (V2 = 5.9 km h^{-1}) treatments (Table 2) show that the slope gradient and mean tillage depth are similar, but the transport coefficient (K) is larger for OA2V1 than for OA2V2. Comparisons between the OA3V1-stubble field (V1 = 3.1 km h^{-1}) and OA3V2-stubble field (V2 = 4.8 km h^{-1}) treatments show a similar tendency. One would expect that in both cases the transport coefficient from OA2V2 and OA3V2 would be greater than the transport coefficient of OA2V1 and OA3V1 because the velocity is higher in the former. On the other hand, comparing the OA2V1-pre-tilled soil (V1 = 1.9 km h^{-1}) and OA2V2-pre-tilled soil (V2 = 3.5 km h^{-1}) treatments (Table 2), the slope gradient and mean tillage depth are similar, but the transport coefficient is higher for OA2V2 than in OA2V1. There is a similar tendency in the OA3V1-pre-tilled (V1 = 3.1 km h^{-1}) and OA3V2-pre-tilled (V2 = 3.4 km h^{-1}) comparisons (Table 2). In both cases, the transport coefficient for OA2V2 and OA3V2 are greater than the transport coefficients of OA2V1 and OA3V1. From these observations, we conclude that the response of soil movement to velocity may be not linear.

Figs. 4 and 5 show the transport coefficients plotted versus the opening angles (OA). The intercepts suggest that opening angles of less than 10° do not produce much soil transport. The figures also show that the regression line slope is higher for the stubble field than for the pre-tilled soil. This indicates that soil transport would be greater in the stubble field, especially for the opening angles of 44° and 59°. As with the 10° angle, the 20° OA did not have a great effect on the soil transport.

A regression equation, statistically significant, for predicting the soil transport coefficient K (kg m^{-1}) was developed (Eq. (1)) using tillage depth (TD, m), speed (SPD, km h^{-1}) and offset opening angle (OA,°). This relationship explains 80% of the data variation with tillage depth speed and offset opening angle contributing 63, 13 and 4%, respectively, to the r^2 value. Fig. 6 shows the relationship between observed and predicted transport coefficients.

$$K = -208.08 + 2582.78 \times \mathrm{TD} + 92.27 \times \mathrm{SPD} + 2.25 \times (\mathrm{OA} - 20^\circ) \quad (r^2 = 0.80,\ n = 12) \tag{1}$$

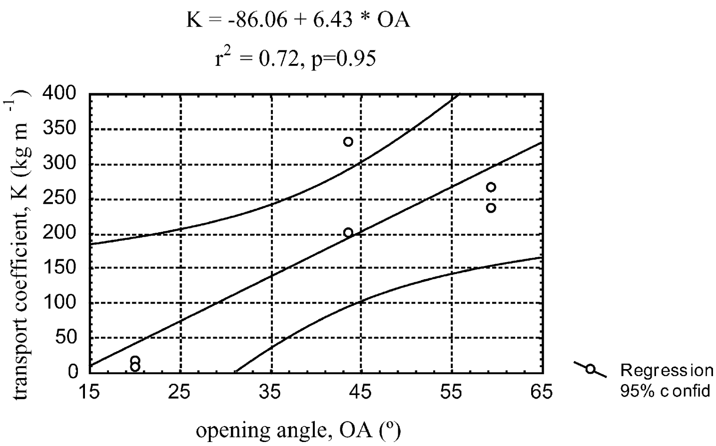

Fig. 4. Offset angle effects on the transport coefficient for a disk harrow in grassland stubble (Site 1).

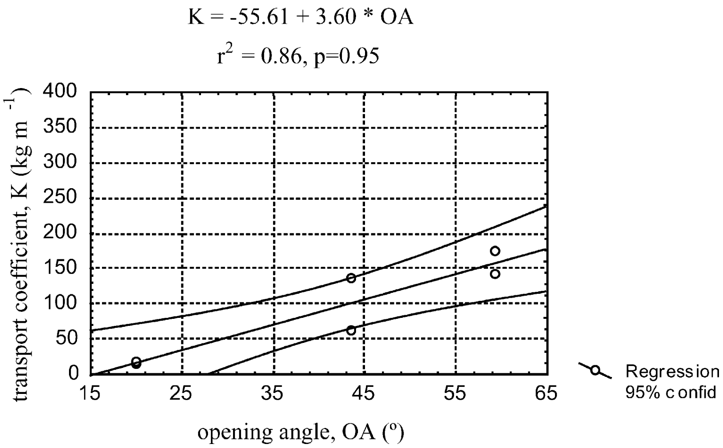

Fig. 5. Offset angle effects on the transport coefficient for a disk harrow in pre-tilled soil (Site 2).

Comparing Eq. (1) with the data in Table 2 the offset opening angle explains only a minor percentage of the K variation (4%), but from the measured data we can observe that the offset opening angle has a big impact on the soil translocation. Conceptually, we would expect that the offset opening angle would explain much more K variation. We believe that this did not occur because the three variables are interrelated and dependent upon each other. For example, at constant tractor power traction if we increase the offset opening angle, tillage depth will increase and speed will be reduced. If we maintain the same offset opening angle and increase speed, tillage depth will be reduced because this is a trailed implement. Therefore, the offset opening angle presumably has a minor impact in Eq. (1) because this variable has an indirect effect on both tillage depth and speed. All these maybe true if we consider that there is no slippage.

Since K values describe the potential of tillage implements to remove soil in convex positions of the landscape and deposit soil in concave positions of the landscape, they provide information on potential soil quality changes caused by tillage-induced erosion with each implement. The soil transport coefficient, K, could therefore be used to rate implements considering their impact on soil translocation. Implement manufacturers could then use this information to construct more environmentally friend implements.Conclusions

Ploughing up- and down-slope with a mouldboard plough produced a net soil translocation in the direction of tillage and perpendicular to the same line. Soil

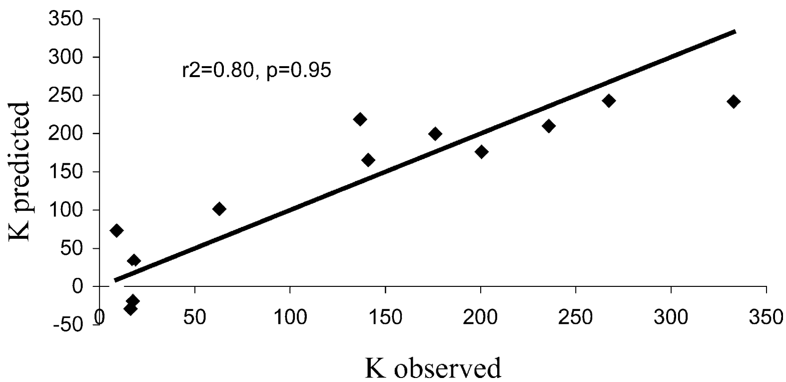

Fig. 6. Observed and the predicted (Eq. (1)) transport coefficients.

transport in the direction of tillage was slope dependent, but transport perpendicular to the line was dependent on the implement. For the mouldboard we used, the soil is shifted laterally 0.45 m, but with other types of mouldboard ploughs this value could be different. More experiments are needed to determine exactly how the mouldboard plough influences lateral soil transport. Tilling up- and down-slope with an offset harrow disk also produced a net soil transport in the direction of tillage. The amount of translocation was slope dependent, but also varied with the soil condition (grassland stubble versus pre-tilled), the velocity of tillage, and the offset opening angle. The stubble field was more susceptible to soil transport than the pre-tilled soil. Also, the greater the opening angle, the greater the soil transport. Velocity was a difficult factor to control and difficult to interpret, the data suggests that the response of soil movement to velocity may not be linear.

Comparing the mouldboard and offset disk harrow, the former has a transport coefficient, that is, 2–3 times greater than the largest disk harrow value. This indicated the mouldboard plough is a more erosive implement than the harrow disk, but if we consider that farmers will often use the disk harrow several times, the total transport coefficient may be the same or even greater than that for the mouldboard. This relationship introduces two definitions that soil quality specialists need to be aware of, which is the "annual tillage transport coefficient" and the "crop rotation tillage transport coefficient". The first one will be the sum of all partial transport coefficients necessary to prepare the seed bed in 1 year and the second one will be the average for the crop rotation. They will differ from crop to crop, agricultural system to agricultural system and from region to region considering the different tillage implements and the number of times that an individual farmer will use them. The annual tillage transport coefficient and the crop rotation tillage transport coefficient may also be useful management indicators to better understand long-term effects of crop production on soil quality.

References

Govers, G., Vandaele, K., Desmet, P., Poesen, J., Bunte, K., 1994. The role of tillage in soil redistribution on hillslopes. Eur. J. Soil Sci. 45, 469–478.

Govers, G., Van Muysen, W., 1999. FAIR3-CT96-1478—"Tillage Erosion: Current State, Future Trends and Prevention" Consolidated Progress Report for the Period From 1 March 1998 to 28 February 1999. Commission of the European Communities, Agriculture and Fisheries (FAIR) specific RTD programme.

Guiresse, M., Revel, J.C., 1995. Erosion due to cultivation of calcareous clay soils on the hillsides of south west France. I. Effect of ploughing down the steepest slope. Soil Till. Res. 35, 157–166.

Heckrath, G., Sibbesen, E., 1999. FAIR3-CT96-1478—"Tillage Erosion: Current State, Future Trends and Prevention" Consolidated Progress Report for the Period From 1 March 1998 to 28 February 1999. Commission of the European Communities, Agriculture and Fisheries (FAIR) specific RTD programme.

Kachanoski, R.G., Rolston, D.E., De Jong, E., 1985. Spatial variability of a cultivated soil as affected by past and present microtopography. Soil Sci. Soc. Am. J. 49, 1082–1087.

Kachanoski, R.G., O'Halloran, I., Lobb, D.A., 1997. A stochastic transfer function model for tillage translocation. J. Soil Water Conserv. 52, 304.

Kosmas, C., 1999. FAIR3-CT96-1478—"Tillage Erosion: Current State, Future Trends and Prevention" Individual Progress Report for the Period From 1 March 1998 to 28 February 1999. Commission of the European Communities, Agriculture and Fisheries (FAIR) specific RTD programme.

Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., 1992. Quantifying tillage erosion rates due to mouldboard plowing. Soil Till. Res. 24, 243–255.

Lobb, D.A., Kachanoski, R.G., Miller, M.H., 1992. Soil loss by tillage erosion: the effects of tillage implement, slope gradient, and tillage direction on soil translocation by tillage. SWEEP/TED Report No. 55. University of Guelph, Guelph, 143 pp.

Lobb, D.A., Kachanoski, R.G., Miller, M.H., 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using ^{137}Cs as a tracer. Can. J. Soil Sci. 75, 211–218.

Lobb, D.A., Quine, T.A., Govers, G., Heckrath, G., 2000. Comparison of methods used to calculate tillage translocation using plot-tracers. J. Soil Water Conserv. 56 (4), 321–328.

Marques da Silva, J.R., Soares, J.M., 1999. FAIR3-CT96-1478—"Tillage Erosion: Current State, Future Trends and Prevention" Individual Progress Report for the Period From 1 March 1998 to 28 February 1999. Commission of the European Communities, Agriculture and Fisheries (FAIR) specific RTD programme.

Marques da Silva, J.R., Soares, J.M., 2001. Spatial variability of soil quality indicators a consequence of soil erosion. In: Soil Erosion Research for the 21st Century Proceedings, January 3–5, Honolulu, Hawaii, USA.

Monreal, C.M., Zetner, R.P., Robertson, J.A., 1995. The influence of management on soil loss and yield of wheat in Chernozemic and Luvisolic soils. Can. J. Soil Sci. 75, 567–574.

Montgomery, J.A., McCool, D.K., Busacca, A.J., Frazier, B.E., 1999. Tillage soil movement and soil degradation in the Palouse

Region of Eastern Washington, USA. Soil Till. Res. 51 (3–4), 175–187.

Poesen, J., Van Wesemael, B., Govers, G., Martinez-Fernandez, J., Desmet, P., Vandaele, K., Quine, T., Degraer, G., 1997. Patterns of rock fragment cover generated by tillage erosion. Geomorphology 18, 183–197.

Quine, T.A., Govers, G., Poesen, J., van Wesemael, B., Walling, D., Martinez-Fernandez, J., 1999. Fine earth displacement by tillage in stony soils in the Guadalentin, south-east Spain: an investigation using caesium-134. Soil Till. Res. 51 (3–4), 279–301.

Quine, T.A., Walling, D.E., Govers, G., 1996. Simulation of radiocaesium redistribution on cultivated hillslopes using a mass balance model: an aid to process interpretation and erosion rate estimation. In: Anderson, M.G., Brooks S.M. (Eds.), Advances in Hillslope Processes. Wiley, Chichester, pp. 561–558.

Revel, J.C., Coste, N., Cavalie, J., Costes, J.L., 1993. Premiers Resultats Experimentaux sur L'Entainment Mecanique des Terres par le Travail du Sol dans le Terrefort Toulousain (France).

Sharifat, K., Kushwaha, R.L., 1998. Soil movement by narrow tillage tools at high speeds. CSAE Paper No. 98-409. Presented at the CSAE Annual Meeting in Vancouver, July 1998, 15 pp.

Sibbesen, E., 1986. Soil movement in long-term field experiments. Plant Soil 91, 73–85.

Turkelboom, F., Poesen, J., Ohler, I., Van Keer, K., Ongprasert, S., Vlassek, K., 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. Catena 29, 29–44.

Van Muysen, W., Govers, G., Bergkamp, G., Roxo, M., Poesen, J., 1999. Measurement and modelling of the effects of initial soil conditions and slope gradient on soil translocation by tillage. Soil Till. Res. 51 (3–4), 303–316.